Hypotable

I. Introduction

Earthquake location programs for events recorded at regional to teleseismic distances have traditionally used travel-time tables, such as the Jeffreys-Bullen tables (Jeffreys & Bullen, 1958) which was based on spherical-earth raytracing in a laterally-homogeneous earth (e.g., Boyd *et al.*, 1984). Such travel-time tables may not give accurate locations for events located with stations at local to near-regional distances because of regional differences in the crustal and upper mantle velocity structure — the regions of the earth in which the first arrival P and S waves spend most of their time for such events. Accordingly, for the past 30+ years, locations for local and near-regionally recorded events have used programs which used flat-earth raytracing through constant-velocity layers. Examples of such programs are Hypo71 (Lee & Lahr, 1972), Hypoinverse (Klein, 1985), Fasthypo (Herrmann, 1979), and Hypoellipse (Lahr, 1999).

With the advent of digital recording and advances in telemetry, there is an increasing number of datasets which include arrival times for small to medium-sized events at both local and regional distances. In 1991 I and my colleagues had such a dataset, so I worked with John Lahr to introduce spherical-earth raytracing as an option to his program Hypoellipse. Lahr subsequently included this option in his official Hypoellipse package, but until now the program for generating the travel-time tables to go with that option had not been made available. This writeup accompanies the release of program Hypotable.

The Hypotable distribution consists of a Unix directory tree with three README files in the top directory which describe the contents of three sub-directories: **iaspei-tau**, which includes the software needed to construct the iasp91 travel-time tables (Kennett & Engdahl, 1991) and program Hypotable; **build-tables**, which has the input and output for building a set of tables in the format to be used in Hypoellipse; and **sample-runs**, which gives a sample application showing how these tables can be used in Hypoellipse. After a section reviewing flat-earth and spherical-earth raytracing, there are short sections on each of these subdirectories. The final section is on a future wish list for further developments and enhancements.

II. Raytracing in a Spherical Earth and a Flat Earth

A review of the math and physics involved in flat-earth and spherical-earth raytracing can be found in most books on geophysics which have sections on earthquake seismology, for example Chapter 5 in the third edition of Stacey's book (Stacey, 1992).

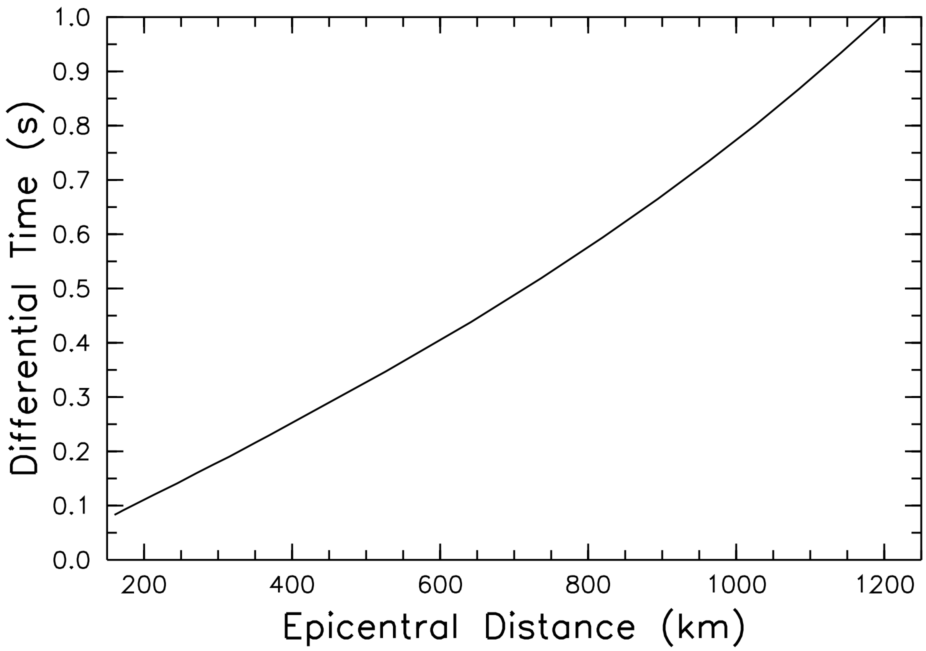
Crustal events

Velocity models for seismically active regions where the seismicity is primarily crustal, are usually developed using local or regional networks and flat-earth raytracing. In a flat-earth model, a downgoing ray can only get to the surface if it is reflected at a velocity discontinuity or if it is critically refracted at the discontinuity and travels along it as a headwave (P_n or S_n). Commonly, the mantle is given as a single layer (or half space), and it enters into travel-time calculations only as the velocity for the flat part of the path of the headwave.

Actual headwaves are not observed in the real earth, but if the epicentral distance is less than a couple of hundred kilometers, the refracted wave does not penetrate very deep into the mantle and the difference between the actual ray path and the arc defining a constant-depth Moho do not differ much, so using a flat-earth velocity model does not lead to a large error — that is, an error greater than 0.1 s.

Typically, only the first P and S arrivals are used when locating earthquakes. For crustal earthquakes, at short distances this will be the direct, upgoing wave (P_g or S_g). At greater distance, because the mantle velocities are higher than crustal velocities, the refracted P_n or S_n waves come in as the first arrivals. The distance at which the arrival times for the upgoing and downgoing rays are the same is called the **crossover distance**. If the P-to-S velocity ratio is not constant with depth, the crossover distances will differ for P and S. The crossover distances will also change with focal depth.

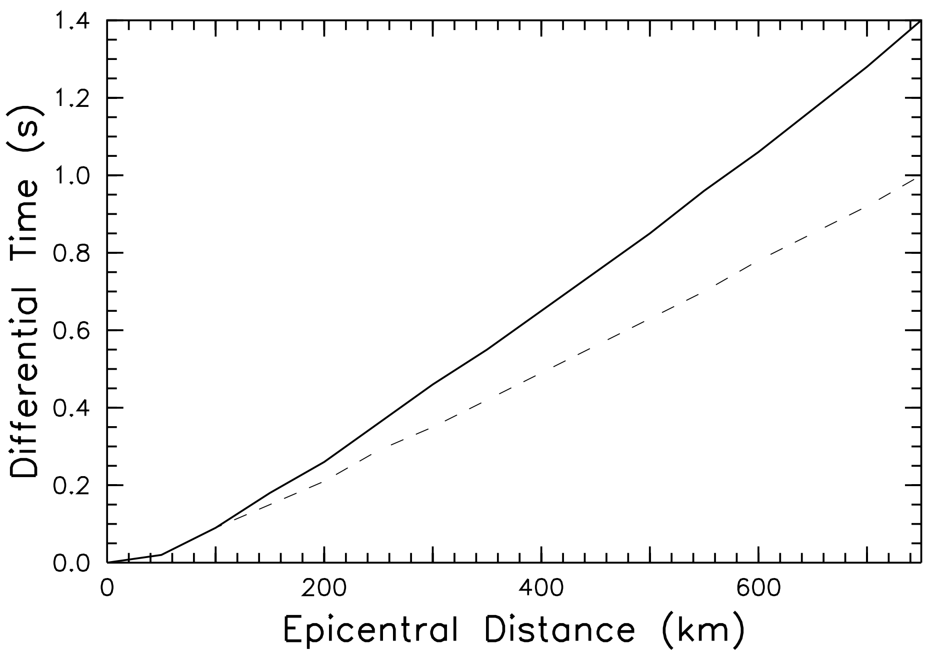
For epicentral distances less than the crossover distance, the flat-earth and spherical-earth arrival times agree to within a couple of hundredths of a second (see example in sample-runs). Beyond that distance, the flat-earth times will become increasingly slower than the spherical-earth times. (For a constant-velocity mantle, this can be explained by the fact that the chords traveled by the spherical-earth ray become increasingly shorter than the path along the Moho traversed by the flat-earth ray.)



Shown above is a plot of differential travel time vs epicentral distance for a surface focus starting at a distance for which the time differential becomes non-negligible. The differential travel time is defined as the flat-earth travel time minus the spherical-earth travel time for the P-wave. Note that for distances greater than 170 km, the error is at least 0.1 s. The dependence of the differential travel time on focal depth is small.

Deep-focus events

The studies I was involved in which led to my writing Hypotable in 1991 involved an analysis of events in the subduction zone beneath western South America (Norabuena *et. al.*, 1994; James & Snoke, 1994). Here the focal depths were 110–155 km, and the epicentral distances for the locator stations were up to 700 km. In principle, it is possible to use earth-flattening transformations for the velocity structure (e.g., Buland & Chapman, 1983), but because most flat-earth location programs require constant-velocity layers, the transformed structure is rarely used.



The above figure show the differential travel times for two focal depths using the iasp91 velocity model. The solid line is for a focal depth of 100 km, the dashed line for a depth of 150 km. Compared to the zero-focus example, the errors become significant at a shorter distance.

III. Compiling and Linking Program Hypotable

The iaspei-tau directory has the source code and executables for the iasp91 travel-time table package (February 1996 version) and program Hypotable. The program ttimes.f differs from the one which comes with the iasp91 distribution in that it includes a few more options, like allowing distances in km and printing a detailed output file in parallel with the terminal output. The source language is Fortran 77, and, as written, compiles on both Sun platforms, sunos 4.1.4 and solaris 2.x. The Unix make file which creates the library libiasp.a and the executables remodl, setbrn, ttimes, and Hypotable is also included, as are the solaris 2.x executables. The -Bstatic option has been used in producing the executables, which increases portability.

The original 1991 release of the iasp91 package and its 1992 update are hard-wired to handle only the iasp91 velocity structure, which it did through polynomial fits within designated layers for the velocities and density. In 1991 I (Arthur Snoke) changed subroutine emdlv.f so that it could read in a v-z model from a file. (In 1992 I replaced the linear interpolation in this subroutine with cubic-spline interpolation.) File iasp91.mod is the iasp91 model in the format expected by emdlv. The February 1996 package added a few core phases and included a variant of my emdlv.f for reading velocity models from files. For more information about the iasp91-tau package, look at README_tau, written (mostly) by Ray Buland.

To create a table, one first runs program remodl. In this version, one needs an xxx.mod file. All other input comes from prompts. The actual table creation (here IASP91.hed and IASP91.tbl) is done by then running program setbrn. Program rsetbrn is a stripped-down version of setbrn which produces tables with a far reduced set of phases – basically only the P and S branches, including all the forward branches for distance ranges for which there are triplications. The tables included here are generated using setbrn. If one is just using the iasp91 tables, these programs need not be run as the (possibly platform independent) IASP91.hed and IASP91.tbl files are included (in directory build-tables. Unfortunately, the code seems to be optimized for the iasp91 model, so table creation for other models may not be stable. (Using rsetbrn rather than setbrn may help.) In my applications, I have not cared about core phases, so I just change the (two-layer) crust and the uppermost mantle while keeping the iasp91 model for the rest of the earth.

Program Hypotable uses subroutines included in libiasp.a. As written, it requires that the .tbl, .mod, and .hed files are all in the directory from which the program is being run.

IV. Creating Tables with Hypotable

Directory build-tables has scripts for creating a set of P- and S-velocity tables using the iasp91 velocity structure, the two tables, and listing files for each table summarizing the input parameters used.

The table format is basically that developed by Klein for his Hypoinverse earthquake location program. Program Hypoinverse assumes a flat-earth velocity structure, and the tables for use in Hypoellipse are generated using Klein's program ttgen and can handle velocity gradients within layers but not first-order discontinuities Program Hypotable was written by me (Arthur Snoke) to allow for spherical-earth ray tracing for locating earthquakes with program Hypoellipse. The table generation uses the iasp91-model software developed by Ray Buland. In principle it can be used with any velocity structure with a two-layer crust, but it is not stable for all such models. This distribution includes only the iasp91 velocity model.

Input required are both the .tbl and .hed files produced by the iasp91 package, as well as the .mod file used to generate those files. These three files are assumed to be in the directory from which the program is run (in this case, directory build-tables). One can either create a single P-velocity table and use a single P/S velocity ratio to calculate S travel times from that table, or create a second S-velocity table, which allows for variations in the velocity ratio with depth. In this distribution, the separate S-velocity-table option is used.

One is prompted for ranges in both depth and epicentral distance (both in kilometers).

One can input up to two ranges in each case: generally one set of ranges with a finer spacing for shallower depths and smaller distances and a second set of ranges for greater depths or distances with coarser spacing. Because Hypoellipse uses interpolation to calculate both the focal depth and event-station distances from these tables, one should fine-tune the ranges based on the focal depths of interest and the event-station distances involved. Two applications I have used these tables for are event locations in the western South American subduction zone where the focal depths were over 100 km, and the location of very shallow rock bursts associated with gold mines in South Africa. For this distribution we include only a set of tables for which the depths are assumed to be shallow.

The scripts for generating the tables in build-tables are self commented. By comparing them with the listing file created and the tables themselves, it should be clear what the entries mean.

V. Sample Runs Using Hypotable Tables in Hypoellipse

The sample-runs directory has drivers, input, and output for Hypoellipse runs for v-z model only, for tables only, and for tables used only beyond a fixed distance (control parameter 51 set to 160.). It is assumed that the executable (called Hypoe here) is in the same directory or is in a directory included in the PATH environmental variable.

The example used here is based on a South African event, but the travel times have been adjusted to give zero error for arrivals based on spherical-earth ray tracing using the iasp91 travel-time tables for the assumed focal depth (2.47 km) and epicenter. The epicentral distances were gotten from a Hypoellipse run with a fixed hypocenter. (Hypoellipse uses spherical geometry when calculating epicentral distances.) The times were calculated using program ttimes, and the output is given in ttimes-iasp91.lst.

The flat-earth iasp91 model contained in crustal-iasp-prm is the iasp91.mod given in other directories except that the upper mantle has been broken into several constant-velocity layers. (This does not matter here, as the Moho heasdwave appears to be the only down-going ray used for these distances.)

To run with tables only requires changing the station list entries so that model 26 is the preferred model (rather than model 1). File stations-tab.dat has been written so that tables only are used. If one wants to use tables beyond a fixed epicentral distance, one uses stations.dat and change control parameter 51 to a distance which will be the transition between the flat-earth model and the spherical-earth tables. One can see exactly which model (or table) was used for each station and phase by looking in the Hypoellipse .out file at the entry for that station and phase under "c" in the *travel times and delays* section.

The systematic error which increases with distance for calculated arrival times based on flat-earth raytracing can be seen by looking at "resid" in the *travel times and delays* sections in the different .out files. For this example for P arrivals using flat-earth ray tracing (iaspvz.out), there is an error of at most 0.01 s for distances up to 135.7 km, but between 171 and 500 km, the flat-earth error increases from 0.1 to 0.33 seconds. For 171 km and greater distances, the table calculations (iasptab.out) differ by at most 0.01 seconds.

However, the method used here for calculating the spherical-earth travel times does not work well near the crossover distance. For this example, at the epicentral distance of 135.7 km the "tables-only" output has an error of 0.05 and 0.03 seconds for P and S respectively. Also, the "ain" (which is the take-off angle from the source measured with respect to the upward vertical) are clearly wrong. For the flat-earth-model version, the errors are only 0.01 s for both arrivals and the values for *ain* are reasonable. The explanation for this discrepancy is that flat-earth raytracing is still okay at this distance, but the interpolation scheme used for tables in the earthquake location programs does not properly take into account the first-order discontinuity in the ray parameter which occurs at the crossover distance (see the "dT/dD" entries for the first arrivals in the file ttimes-crossover.lst). Note that for this focal depth and the iasp91 velocity model, the P and S crossovers differ by about 8.5 km — 148.2 km for P, 156.7 km for S.

Because the flat-earth raytracing is still adequate at the crossover distance, the problem with the tables at this distance can be solved by using the flat-earth raytracing up to the crossover and the tables for distances beyond the crossover. As written, one needs to set manually control parameter 51 to that distance. This is what is done in the run leading to output file iasptabmod.out and summary file iasptabmod.summary. For that run, none of the arrival time errors are greater than 0.01 s.

VI. Possible Future Developments

The sample runs show that the tables lead to errors in both travel times and the take-off angle for distances near the crossover distance. For now, the suggested way to deal with this is to set control parameter 51 in Hypoellipse to the crossover distance. The crossover distance for each table depth is stored in the table, and the program calculates it for the current focal depth. Hence, a possible programming option could be to set control parameter 51 to that value if tables are to be used at all, and/or to adjust the interpolation scheme to take into account the discontinuities at the crossover distance.

A second approach is to take advantage of the sophisticated interpolation methods used in the iasp91 software and replace tables generated by Hypotable with calls like those used in program ttimes. Unfortunately the iasp91 software package is not robust for models which differ from the iasp91 model. An alternative package has recently been introduced, *The TauP Toolkit* (Crotwell *et. al.*, 1999). However, although these programs appear to be more robust than the iasp91 software, the package is written in Java, so would require a programmer who is comfortable in both Java and Fortran.

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